§25. Anomalous Transport Coefficient for L-mode Plasma in Tokamaks

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The renormalized equation for the dressed test mode is derived by renormalizing the ExB nonlinearity for the fluctuations in tokamaks [1]. This equation is solved by the help of the ballooning transformation to the η coordinate. The dispersion relation for high-n ballooning mode is given as [2]

$$\frac{d}{d\eta}\frac{F}{\hat{\gamma}+\Xi F+\Lambda F^2}\frac{d\varphi}{d\eta} + \frac{\alpha[\kappa+\cos\eta+(s\eta-\alpha\sin\eta)\sin\eta]\varphi}{\hat{\gamma}+XF} - (\hat{\gamma}+MF)F\varphi = 0 \qquad (1)$$

Terms Λ, X, and M represent the impact of the renormalized turbulence as $\Lambda = \hat{\lambda}n^4q^4$, $X = \hat{\chi}n^2q^2$ and $M = \hat{\mu}n^2q^2$. Ξ stands for the influence of the resistivity, $\Xi = n^2q^2/\hat{\sigma}$. Here normalization is used as $r/a \to \hat{r}$, $t/\tau_{Ap} \to \hat{t}$, $\chi\tau_{Ap}/a^2 \to \hat{\chi}$, $\mu\tau_{Ap}/a^2 \to \hat{\mu}$, $\lambda\tau_{Ap}/\mu_0 a^4 \to \hat{\lambda}$, $\tau_{Ap}/\sigma\mu_0 a^2 \to 1/\hat{\sigma}$ and $\gamma\tau_{Ap} \to \hat{\gamma}$. τ_{Ap} is the poloidal Alfven velocity $\tau_{Ap} = a\sqrt{\mu_0 m_i n_i}/B_p$, B_p is the poloidal magnetic field Br/qR, $\varepsilon = r/R$, $s = r(dq/dr)/q$, $\beta = \mu_0 n_i(T_e+T_i)/B^2$, $\kappa = -\varepsilon(1-1/q^2)$, $F = 1+(s\eta-\alpha\sin\eta)^2$, and $\alpha = -q^2R\beta'$ denotes the normalized pressure gradient. If one neglects the anomalous transport coefficient, Eq.(1) reduces to that for the resistive ballooning mode, and the ideal MHD mode equation is obtained by taking $1/\sigma=0$. The equation (1) constitutes the nonlinear dispersion relation. It can be shown that the growth rate behaves, in the limit of small transport coefficients, as $\gamma \propto \lambda^{1/5}$ showing that even the small amount of the current diffusivity can give a large nonlinear growth rate. Since λ is proportional to ϕ^2 in the small amplitude limit, the growth rate is strongly deformed from its linear prediction under the finite amplitude turbulence.

The stability boundary for the least stable mode is given in terms of the pressure gradient. We introduce a normalized pressure gradient, Itoh number, in analogy of the Rayleigh number in the fluid dynamics, as

$$\Im = \frac{\alpha}{f(s,\alpha)^{2/3}\hat{\mu}^{1/3}\hat{\chi}\hat{\lambda}^{-2/3}} \qquad (2)$$

The stability condition is given as $\Im \le 1$. The marginal stability condition gives the transport coefficients as

$$\alpha = f(s,\alpha)^{2/3}\hat{\mu}^{1/3}\hat{\chi}\hat{\lambda}^{-2/3} \qquad (3)$$

where the coefficient $f(s,\alpha)$ stands for the influence of the magnetic shear.

Using the level of self-sustained turbulence, the anomalous transport coefficient in the L-mode plasma is obtained. The Prandtl numbers, μ/χ and μ_e/χ, are close to unity. Taking the estimation that $\mu/\chi = 1$ and $\mu_e/\chi = 1$ (i.e., $\lambda/\chi = (\delta/a)^2$, δ being the collisionless skin depth), the anomalous transport coefficient is given From Eq.(6) as

$$\chi = \frac{q^2}{f(s,\alpha)}(-R\beta')^{3/2}\delta^2\frac{v_A}{R} \qquad (4)$$

The function f is fitted as $0.4\sqrt{s}$ in the strong shear limit, and approximated as

$$f(s,\alpha) = (1+2\alpha-2s)\sqrt{\{2+6(s-\alpha)^2/(1+2\alpha-2s)\}}$$

in the weak/negative shear limit.

This form of χ is consistent with various aspects of the L-mode transport characteristics, i.e., (a) τ_E is approximately proportional to $I_p \ell_i A^{0.2} P^{-0.5}$ (I_p: plasma current, ℓ_i: internal inductance, A: ion mass, P: heating power) (b) large χ near the edge, (c) weak dependence of temperature profile on the heating profile, (d) larger χ^{HP} than χ^{eff}, (e) μ is enhanced to the level of χ, (f) reduction of χ by negative or very small shear and so on.

References

1) Itoh K, et al.: Phys. Rev. Lett. **69** (1992) 1050
2) M. Yagi et al.: Phys. Fluids B**5** (1993) 3707